A relation between the dark mass of elliptical galaxies and their shape

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It has been reported that there appears to be little non-baryonic dark matter in some elliptical galaxies. We have studied a large number of elliptical galaxies and found a clear, previously unknown, correlation between their dark matter content and the ellipticity of their visible shape. At equal luminosities, flattened medium-size elliptical galaxies have on the average five times larger total mass than round ones. Such a correlation provides a new testing ground for models of dark matter and galaxy formation.

Dark matter cosmology has been successful at determining many large-scale features of the universe [1] but open questions remain at the galactic and semi-galactic scales [2, 3]. There, galaxies are described as made of large dark matter halos surrounding smaller luminous components. A search for relationships between the observed luminous matter of a galaxy and its dark matter content can potentially advance our understanding of dark matter cosmology at this scale. Useful and intriguing empirical correlations have been found, for example the Tully-Fisher relation [4] for spiral galaxies, which relates their rotation speed to their absolute luminosity, or for elliptical galaxies, the Fundamental Plane [5] which includes the Faber-Jackson [6] and Kormendy [7] relations and links their effective radius R_{eff}, their surface brightness and σ, the statistical dispersion of stellar velocities. However, none of these involve directly the dark matter content of galaxies. There is also the puzzling observation of little dark matter content in some elliptical galaxies [8]. We report here on a search for a correlation between the most obvious visible characteristic of elliptical galaxies, the ellipticity, on which their Hubble classification is solely based, and their relative amount of dark matter, expressed as the galactic total mass (dark+luminous) normalized to luminosity (M/L).

Although elliptical galaxies can have tri-axial ellipsoidal shapes and ellipticities depending on radii, to first approximation their geometric shapes can generally be simply parameterized as oblate ellipsoids of constant ellipticities (ε). These span a large range, from spheres ($\varepsilon = 0$) to flattened ellipsoids ($\varepsilon = 0.7$), providing us with a group of smoothly varying shapes. However, only the projection of ε on our observation plane (the apparent ellipticity, ε_{app}) can be measured, their true ellipticity (ε_{true}) remaining elusive. In addition the M/L ratio for ellipticals is hard to measure accurately [8]. To overcome these difficulties, we select large and homogeneous samples of elliptical galaxies for which M/L has been extracted using different methods. Effects of galaxy peculiarities are minimized by a homogeneity requirement and suppressed statistically. The projection problem is addressed statistically. We select 255 different galaxies for a total of 685 data points from 40 publications. Each provides M/L (or related ratios) for at least several galaxies, allowing us to study subgroups of data with consistent M/L extraction. From each publication, we select a sample of elliptical galaxies as homogeneous as possible to avoid diluting (by including effects particular to a galaxy) or biasing any possible correlation (via systematic effects from a class of galaxies, e.g. compact or giant ellipticals). Only medium-size elliptical galaxies are considered. These tend to have nearly isotropic random velocities (contrary to e.g. giant ellipticals). We require undisturbed galaxies to avoid galaxy-galaxy interaction from invalidating the method used to extract M/L (e.g. virial theorem, equations of hydrostatic equilibrium or strong lensing equations). The strict selection applied to samples of local galaxies must be relaxed for samples of distant galaxies, since those are not as well characterized. (Distant galaxies are typically considered in strong lensing studies or in studies of the Fundamental Plane time-evolution, see e.g. [9]). The local and distant rejection criteria are as follows (based on either NASA/IPAC Extragalactic Database (NED) [10] or the publication from which M/L originates):

Classes of rejected local galaxies:

•Lenticular galaxies (S0-type).

•Transition-type (E+), spiral galaxies.

•Galaxies having an Active Galactic Nucleus (AGN) since, for mature galaxies, it may reveal that the galaxies have been disturbed recently.

•Seyfert galaxies and BL Lacertae objects, for the same reasons as AGN.

•Peculiar galaxies and galaxies listed in the Arp Atlas of Peculiar Galaxies.

•Galaxies with HII emission, since the presence of HII regions is peculiar for ellipticals. Furthermore, it may reveal a recent disturbance. It may also bias M/L since newly formed blue stars increase the luminosity.

•Galaxies with low-ionization nuclear emission-line regions (LINER) since they may be due to AGN or star births, in both cases a sign that the elliptical galaxies have been disturbed.

•Compact ellipticals since they belong to a different class of ellipticals.

•Supergiant ellipticals (cD), giant ellipticals (D), Brightest Cluster Galaxies (BrClG) since they belong to different classes of ellipticals. Furthermore, giant ellipti-

cals are characterized by more anisotropic random velocities and tend to be triaxial. In addition, the dark matter of the cluster or group to which these galaxies belong may contribute to the galaxy dark matter content [11].

•E? galaxies. We assume that this lack of nomenclature knowledge reflects poor measurements and may contaminate the sample with non-ellipticals.

•Bright X-ray and very faint X-ray galaxies. Very faint X-ray galaxies show signs of disturbed hydrostatic equilibrium [11]. In the case of bright X-ray galaxies, the hot gas property merges with the extragalactic gas of the group/cluster, indicating some influence from the environment and a contribution of the group/cluster dark matter to the galaxy M/L [11]. In addition, these galaxies tend to be cD, D or BrClG.

We keep low excitation radio galaxies and weak emission-line radio-galaxies as we have seen no reason to reject them. In some cases, when the statistics are low, we have relaxed some of these selection criteria (typically keeping LINER galaxies). In that case, the analysis is considered to be of lower reliability. This, together with the smaller statistics, makes these analyses contribute little to the final result.

Classes of rejected distant galaxies:

•Massive galaxies, typically with $M \gtrsim 5 \times 10^{11}\mathrm{M}_\odot$, to reduce the amount of cD, D or BrClG galaxies.

•Galaxies with velocity dispersions $\sigma \leq 225$ km.s^{-1}, if no distinction is made in the publications between S0 and elliptical galaxies, or if the classification is not reliable enough. This is to suppress possible S0 contamination, since S0 tend to have $\sigma \leq 225$ km.s^{-1}.

We remark that the rejection criteria have been chosen before performing the analysis. In this sense, the analysis is blind and as free of subjective bias as possible.

We use data from six different categories of methods used to deduce M/L. This mitigates the possibility of a systematic methodological bias. These are:

•Virial theorem: We employ virial data from 8 publications [9, 12, 13, 15]. For cases where published analyses do not allow for ellipticity, we correct them using the tensor expression given in [13]. (This important correction derived analytically was experimentally verified in [14].)

•Stellar dynamics modeling: We use 11 publications [16, 17]. An advantage of this method is that ε_{true} can be inferred and used directly in calculations.

•Interstellar gas X-ray emission data: The 2 publications we used [11] assume spherical symmetry. We can partly account for ellipticity by replacing Newton's Shell Theorem (used in the derivation of the equation of hydrostatic equilibrium) by a relation including ellipticity. This yields a correction numerically similar to the tensor correction [13] to the scalar virial theorem.

•Planetary Nebulae and Globular Clusters data: The 4 publications used here [8, 18] assume spherical symmetry. To account for ellipticity, we note that the ellipticity corrections to the virial and Shell theorems are close and apply the same correction.

•Gas disk dynamics: We use 3 publications [19, 20].

•Strong lensing: We use 16 publications [2, 21, 22]. Effects of ε are expected to be small [21] and no correction is applied.

Clearly, from such varied methods of determining M/L, different correlations with ellipticity can result depending on the treatment of ε, systematic modeling biases, or sampling biases. For example, strong lensing tends to sample more massive galaxies, whose corresponding $M/L(\varepsilon)$ correlation strength may differ from those of medium-mass galaxies. It is to minimize such particular biases that we employ all available methods.

Linear fits of M/L to ε are carried out for each of 40 homogeneous samples. The fit results are then combined, which reveals a significant correlation between M/L and ε. Results from 4 out of the 40 samples are shown on FIG. 1. The large scatter results from the random projection of the elliptical galaxies on our observation plane. However, all slopes indicate a positive correlation, with 4.4, 4.3, 1.3 and 1.2 σ deviation from zero, from top left to bottom right panels respectively. (Fits of M/L without accounting for ε, i.e. using straight horizontal lines, yield χ^2/ndf values that are 1.5, 1.3, 1.1 and 1.1 time larger, respectively.)

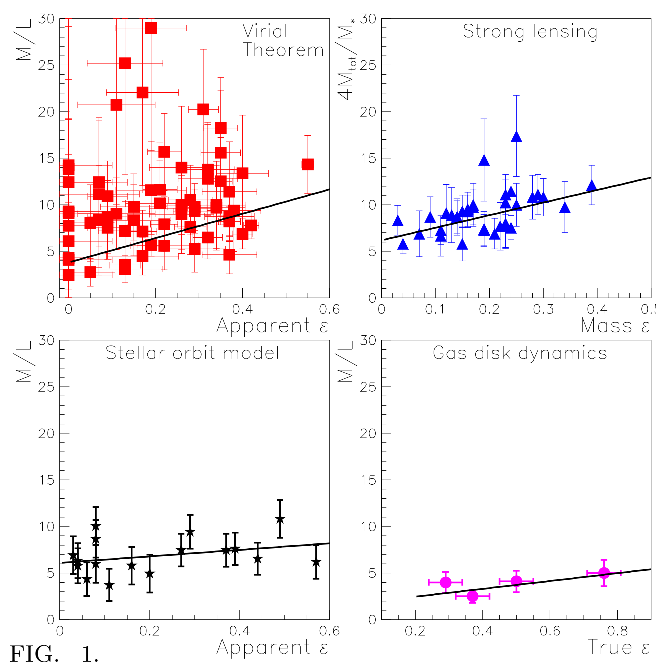

FIG. 1. Galactic mass over luminosity in solar $\mathrm{M}_\odot/\mathrm{L}_\odot$ units versus ellipticity from four publications using different methods. We show some of the most statistically precise and systematically accurate results within each method. Top left: virial theorem [13]. Top right: strong lensing [2] (we plot 4 times the total mass over the stellar mass $4M_{tot}/M_* \simeq M/L$). Bottom Left: stellar orbit modeling [17]. Bottom right: gas disk dynamics [20].

A difficulty with elliptical galaxies is that we observe only their projection, with their true ellipticities being unknown. However, the orientation of galaxies with respect to us is random. Hence, the ε_{true} distribution can be computed from the ε_{app} distribution and the projection corrected on a statistical basis. This correction is independent of the M/L extraction method if the ellipticity distributions in the galaxy samples are the same. We assume so and apply an identical correction to all the data sets (except for those already using ε_{true}, as for example in the bottom right plot of FIG. 1). We use the ε_{app} distribution and M/L versus ε_{app} correlation obtained from [13] to estimate the correction because it is the second largest sample of galaxies (the largest sample is from [15] but the authors indicate it may be slightly biased). The relation between ε_{true} and ε_{app} for an oblate spheroid viewed at an angle i is:

$$\varepsilon_{app} = 1 - \sqrt{(1-\varepsilon_{true})^2 \sin^2 i + \cos^2 i}. \quad (1)$$

We assume a Gaussian distribution for ε_{true}. Its characteristics are chosen so that the simulated ε_{app} distribution reproduces the observed one. The projection correction depends on the relation between M/L and ε_{true}. The simplest assumption is a linear relation. We can also use a Bose-Einstein function to avoid possible unphysical negative M/L near $\varepsilon_{true} = 0$. The distribution of M/L with ε_{app} can then be obtained from the Gaussian distribution transformed using Eq. (1) in which i is random. We also add a random shift toward smaller ε_{app} values to simulate the rounding effect of detector resolution. The initial linear or Bose-Einstein function values have been chosen so that the distribution of M/L with ε_{app} reproduces the experimental results. The fitted slope compared to the initial function's slope provides the projection correction. It increases $\frac{d(M/L)}{d\varepsilon}$, the slope of M/L with ε, by a factor 1.9±0.3. We must apply this factor to M/L ratios extracted using ε_{app} when they are combined to ratios extracted using ε_{true}.

Combining all results requires some caution. Most but not all M/L are extracted in the blue part of the electromagnetic spectrum, the B-band. There are scale factors between B-band results and those extracted in other frequency bands. Other scaling factors occur if authors used different Hubble constant values. Finally, sometimes M_{tot}/M_* is provided (M_* is the stellar mass) rather than M/L (see e.g. the top right plot of FIG. 1) but M_{tot}/M_* is approximately proportional to M/L in most studies. To address these points, we normalize to $M/L(\varepsilon_{app} = 0.3) \equiv 8\mathrm{M}_\odot/\mathrm{L}_\odot \equiv 4M_{tot}/M_*(\varepsilon_{app} = 0.3)$. The values $M/L = 8\mathrm{M}_\odot/\mathrm{L}_\odot$ and $M_*/L = 4\mathrm{M}_\odot/\mathrm{L}_\odot$ are typical in the B-band for elliptical galaxies. We normalize at $\varepsilon_{app} = 0.3$ because the ε_{app} distribution peaks there and it avoids uncertain extrapolations which would be needed if, for example, we were to normalize at $\varepsilon_{app} = 0$. Another caution point is that some publications use similar methods to extract M/L and these have quoted results for common galaxies. For example, the galaxy NGC7619 is used in 4 of the 8 publications employing the virial theorem. Consequently, their results may be correlated and bias the average. In addition some of the M/L extractions are, in our context, more reliable than others. To address this, the uncertainties are multiplied by a reliability factor. (This prescription allows some subjectivity but happens to have small influence, the less reliable results having usually also less statistics.) For extractions using similar methods, we count the common galaxies and increase each uncertainty accordingly assuming that they are statistically dominated. (In doing so, we must account for the reliability factors since results are weighted by them when combined.) This procedure assumes that results using a given method and an identical galaxy sample are perfectly correlated, which is not exact since within similar methods different assumptions, profiles, input distributions, etc... are used. The specific analyses also differ in details and the data quality varies as the publications used span a range of 30 years. Thus, our procedure overestimates the uncertainties. This is partly mended by fitting $\frac{d(M/L)}{d\varepsilon}$ versus radius with a one parameter function (i.e. $\frac{d(M/L)}{d\varepsilon}$ is taken to be constant with radius) and scaling the uncertainties so that $\chi^2/ndf = 1$. Forcing $\chi^2/ndf = 1$ is justified because the results are from either different methods (for which we can assume that their systematic uncertainties are uncorrelated) or, for results using the same method, because we have accounted for the correlation. Although accounting for common galaxies and different reliability is necessary to average as accurately as possible, the net effect happens to be numerically unimportant. Finally, for M/L extracted using strong lensing, $\frac{d(M/L)}{d\varepsilon}$ can be computed using either ε_{app} or mass ellipticity ε_{mass}. This later is the ellipticity of the modeled total mass distribution. We use ε_{app}, as we do for the other five methods. We note however that 8 out of the 10 strong lensing publications for which ε_{mass} is available display a stronger M/L versus ε_{mass} correlation, i.e. $\frac{d(M/L)}{d\varepsilon_{app}} < \frac{d(M/L)}{d\varepsilon_{mass}}$.

The slopes $\frac{d(M/L)}{d\varepsilon_{true}}$ are shown in FIG. 2, plotted for clarity against the approximate average radii at which the M/L values have been extracted. (Some papers provide M/L calculated at different radii, so several points may correspond to one publication. Also, a few outlying points are outside the graph range. Consequently, there are more than 40 points in FIG. 2.) One notices systematic shifts between results using different methods, most noticeably between the strong lensing and virial results. This may be due to the different radii at which the M/L values are extracted. Also, a looser selection is applied on the distant -and thus less characterized-strong lensing galaxies, so contamination may dilute the correlation. In addition, no ellipticity correction is applied because their extracted M/L are less sensitive to ε. Interestingly, if we were to consider $\frac{d(M/L)}{\varepsilon_{mass}}$ rather than

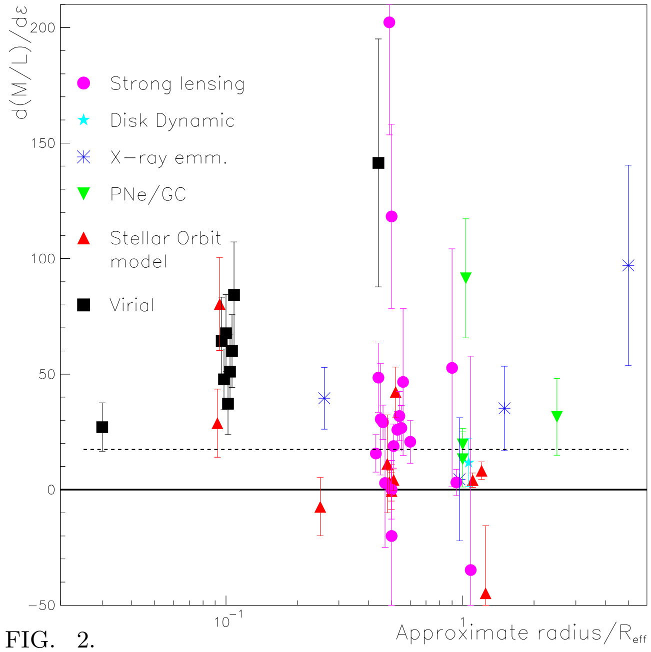

FIG. 2. Slopes $\frac{d(M/L)}{d\varepsilon_{true}}$ versus approximate radii (units of R_{eff}) at which the M/L are extracted. The six symbols distinguish the methods used to obtain M/L. The dash line indicates the weighted average value after accounting for correlations.

$\frac{d(M/L)}{\varepsilon_{app}}$, the strong lensing and the corrected virial results would be consistent. Finally, strong lensing galaxies tend to be more massive, so the comparison with our samples of local galaxies is not direct. Nonetheless, all the averaged $\frac{d(M/L)}{d\varepsilon_{true}}$ from the six different methods are non-zero and positive. They average to,

$$\left\langle \frac{d(M/L)}{d\varepsilon} \right\rangle = (17.42 \pm 4.30)\mathrm{M}_\odot/\mathrm{L}_\odot,$$

a statistically meaningful positive signal, indicating that M/L and ε correlate. We note that, without the selection criteria, the otherwise clear correlation is obscured by large fluctuations, which may explain why it has not been noticed earlier. We verified that it disappears when no selection is applied. The correlation scales with our normalization $M/L(\varepsilon_{app} = 0.3) = 8\mathrm{M}_\odot/\mathrm{L}_\odot$. Compared to $8\mathrm{M}_\odot/\mathrm{L}_\odot$, the slope is large.

An M/L correlation with ε might reveal a significant bias in the data and/or methods. However we have made a thorough investigation of the various inter-dependences of the many variables characterizing elliptical galaxies and found that they could not explain the correlation seen. In addition, the six methods that have been used to extract M/L are independent. This indicates that the correlation is physical rather than a methodological, observational or instrumental bias. Its large magnitude makes it a feature that future descriptions of elliptical galaxies -including their dark matter content- must be able to reproduce. Numerically, with our normalization $M/L(\varepsilon_{app} = 0.3) = 8\mathrm{M}_\odot/\mathrm{L}_\odot$, the correlation indicates that the most flattened medium-size elliptical galaxies have M/L averaging to $(15.0\pm1.8)\mathrm{M}_\odot/\mathrm{L}_\odot$ and the round ones to $(2.8\pm1.2)\mathrm{M}_\odot/\mathrm{L}_\odot$. Since in the B-band, the stellar mass over luminosity is $M_*/L \simeq 4\mathrm{M}_\odot/\mathrm{L}_\odot$, this implies that within the radius investigated (typically 0.1 to 1 R_{eff}), round medium-size elliptical galaxies have small amounts of dark matter (including in particular those considered in [8]). This is puzzling in light of the conventional model of cosmological structure formation, which requires dark matter seeds to trigger galaxy formations.

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